# Is a Resource-Mars a Stepping-Stone to Human Exploration of the Solar System?

**Michael D. Max,** [727-821-3993] <mmax@mdswater.com> MDS Research, 1601 3rd St. South, St. Petersburg, FL 33701

**Stephen M. Clifford,** Lunar & Planetary Institute, 3600 Bay Area Blvd., Houston, TX 77058

**Arthur H. Johnson,** Hydrate Energy International, 612 Petit Berdot Dr, Kenner, LA 70065

**Jeremie Lasue**, Lunar & Planetary Institute, 3600 Bay Area Blvd., Houston, TX 77058

From the time of the first spacecraft flyby of Mars in 1965 until the late 1970s, Mars has been characterized as a resource-poor planet whose thin $CO_2$ atmosphere and numerous craters made it seem more closely related to the Moon than the Earth (Mutch et al., 1976). This early view of Mars was not encouraging for near-term human exploration because all the materials required for a voyage to Mars and establishing a base there would have had to be transported from Earth, including the fuel for the return trip.

More recent spacecraft investigations have dramatically changed this view. Although the surface appears barren, a large amount of water ice is present at both poles as extensive (~1000 km diameter) layered deposits as much as ~3-4 km deep (Picardi et al., 2005; Plaut et al. 2007). There is also geophysical evidence that ice is widespread in the shallow (top meter) subsurface at mid- to high-latitudes (Boynton et al., 2002) and may be present at greater depths elsewhere on the planet (Clifford, 1993).

Estimates of the total inventory of water on Mars are based in part on the amount of water required to produce the enormous scours associated with the Martian outflow channels (Carr, 1996). These erosional depressions – which are tens of kilometers wide, hundreds of kilometers long, and up to 1-2 km deep -- generally emanate full-born from localized regions of collapsed and disrupted terrain. The scale of the braided and streamlined forms found within their beds, combined with the absence of any identifiable tributaries, indicate an origin by catastrophic floods, apparently fed by the catastrophic discharge of subpermafrost groundwater (Baker et al., 1992, Max & Clifford, 2001). The total inventory of water on Mars has been estimated as equivalent of a global layer ~0.5 to ~1 km deep (Carr, 1986, 1996).

The growing evidence for abundant water, combined with the *in situ* and remote detection of evaporites (such as sulfates, gypsum, carbonate), various salts, metals (Fe, Mg, Ti, Na and Al), and, most recently, large plumes of atmospheric methane (Mumma et al., 2009), have led to a substantial revision of the resource characterization of Mars. These materials are the basic feedstock of the modern chemical engineering industry and could be harvested and utilized to support and expand the human exploration of Mars and beyond (Zubrin, 1996; Fergus, 2003).

A new paradigm of a resource-rich Mars should now be considered central in planning for future human travel to Mars – where Mars is no longer simply a remote, dead-end destination but rather a self-sustaining outpost that can serve as a stepping stone to the exploration of the asteroids and outer Solar System. Mars has the natural resources to make plastics, metals, and many other materials necessary for the sustainable presence and expansion of human settlements (Max and Clifford, 2000, Pellenbarg, et al., 2003).

The question is no longer “does Mars have resources?”, but rather, ”how do we assess and exploit these natural resources?”, and ”how will they affect the human exploration of Mars and beyond?” We now have the ability to utilize the natural resources of other planets and moons to sustain the human exploration of space. It’s time to go.

**Methane in Subsurface Mars**

The possibility that an abundant supply of hydrocarbons may be stored in the Martian subsurface is supported by the apparent subsurface origin of the methane recently detected in the Martian atmosphere (Formisano et al., 2004; Krasnopolsky et al., 2004; Mumma et al., 2004, 2009). Various studies suggest that large quantities of methane may have been produced – either biogenically or abiogenically – within the subsurface. As on Earth, once methane is produced, some may become trapped in the subsurface where it may be affected by local physical and chemical processes, while the remainder will migrate through primary and secondary porosity paths, ultimately to be vented to the atmosphere. When subsurface methane is trapped as gas, under pressure, in the presence of water or ice, it can form methane hydrate (clathrate) (Max et al., 2006; Kargel and Lunine 1998; Fisk and Giovannoni, 1999; Max and Clifford, 2000). Sequestration of only a small proportion of this methane gas flux over a long period of time could result in the production of very large reserves, representing both a potential source of energy and supply of hydrocarbons for the production of chemicals and other raw materials.

On Earth, the conditions necessary for the formation of natural gas hydrates are found at depth in permafrost and beneath the ocean in continental margin sediments. Marine methane hydrate, at least that found along the tectonically passive eastern margin of North America, appears to be underlain by an active community of anaerobic methanogenic bacteria (Wellsbury and Parkes, 2003). The isotopic composition of marine methane hydrate is almost always dominated by evidence of bacterial production in the Earth’s deep biosphere. But methane can also be produced abiogenically, as a fractionation product of magma crystallization or by reactions with basalt or carbonate in subpermafrost aquifers – yielding local partial pressures ranging up to many bars, depending on local permeability conditions and the availability of both carbon and water. Whatever its origin on Mars, as the planet’s internal heat flow has declined with time, the resulting downward propagation of the freezing-front at the base of the cryosphere would have resulted in the incorporation any subsurface methane as hydrate -- in concentrations that may have ranged from a dispersed contaminant, to massive deposits (Max and Clifford, 2000).

In permafrost regions on Earth, methane hydrate and water ice form a compound cryogenic zone whose extent is determined by the local mean surface temperature, geothermal gradient, and the increase in confining pressure that occurs with depth. A Gas Hydrate Stability Zone (GHSZ) occurs within the region of the crust that satisfies these criteria, below which methane persists solely as a gas (Dickens et al., 1997; Max and Clifford, 2000; Max, 2003; Kargel et al., 2007). A similar zone is defined by the subsurface temperature and pressure conditions found on Mars (Figure 1) (Max and Clifford, 2000; Clifford et al., 2009).

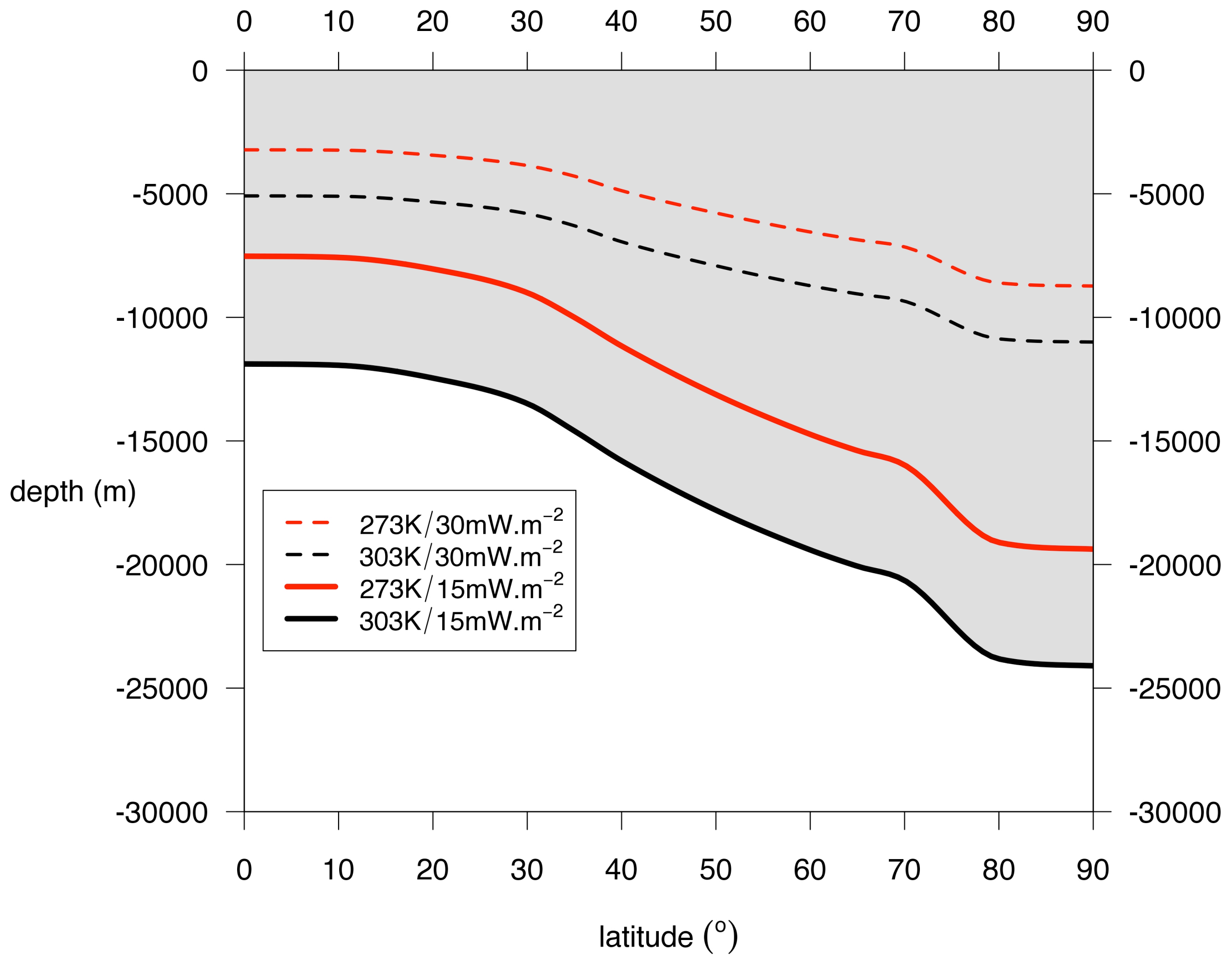


Figure 1. Schematic diagram of a hydrocarbon system for Mars, illustrating the relative positions of the base of the water ice cryosphere (red lines) and gas hydrate stability zone (black lines) assuming a mean global geothermal heat flux of 15 mW m$^{-2}$ (solid lines) and 30 mW m$^{-2}$ (dashed lines) Figure adapted from Clifford et al. (2009).

At the 200 K average surface temperature of Mars, methane hydrate is not stable at a confining pressure of less than ~140 kPa (Sloan, 1997) although, at the colder temperatures characteristic of latitudes >60°, it may be found at considerably shallower depths. Given a reasonable estimate of the thermal properties of the Martian crust, the base of the GHSZ is expected to vary from ~5-12 km at the equator, to ~11-24 km at the poles (Figure 1, se also Clifford et al., 2009); although the base of the GHSZ may occur at much shallower depths where there is active methane venting (Max et al., 2006) or enhanced local geothermal activity. While the size of the GHSZ can be estimated, the extent to which this stability zone is actually populated with hydrate is unknown.

Hydrate does not necessarily remain stable once it has formed. Methane hydrate, as are other hydrates formed from a single hydrate forming species, are governed by very reversible reactions. That is, under pressure-temperature conditions of hydrate stability, if the vapor

pressure of the hydrate-forming material in the aqueous media is higher than in the hydrate, hydrate will accrete. If the vapor pressure is lower, the hydrate forming molecules will diffuse from the hydrate to the surrounding media. That is, if the concentration of dissolved gas falls below a certain level, the hydrate dissolves without forming a gas phase. This is fundamentally different from dissociation, which is caused by altering temperature and/or pressure to conditions outside of the hydrate's stability field (Max et al., 2006). One of the reasons why $CO_2$ hydrate is so rare on Earth is that $CO_2$ is much more soluble in water and its concentration has to be much higher for it to form than methane hydrate.

One possible explanation for the observation of localized sources of atmospheric methane (Mumma et al., 2009) is that they are vents associated with local fault or joint systems, which may provide conduits from reservoirs of methane gas, trapped beneath the BGHSZ, to the surface. In such a leaky system, methane gas migrates upward slowly and irregularly, due to its buoyancy either as a gas or dissolved in a fluid. The concentration of gas dissolved in water becomes more saturated as the water rises and the hydrostatic pressure decreases. At some point a separate gas phase is formed, potentially accelerating the continued upward flow of fluid and gas.

Venting has the potential to advect heat upward from beneath the cryosphere. In doing so, it can result in an 'up-doming' of the isotherms in the vicinity of the vents, thinning the regions where both ice and methane hydrate are stable (Figure 1). On Earth, in the northern Gulf of Mexico, a number of methane vent sites have been extensively studied as part of an assessment of natural gas resources that utilized seismic data, seafloor sampling, drilling, and heatflow measurements, as well as measurements of the temperature and composition of the vent fluids (Max et al., 2006). In regions where the GHSZ exhibits an otherwise uniform thickness, the focused upward flow of relatively warmer gas and fluid along fractures from depth introduces heat into the region surrounding the vent and distorts the regional geotherms. A hydrate-free halo is defined by thermal conditions in which the methane hydrate surrounding the vent is unstable, creating a bell-shaped thermal anomaly centered on the vent. This anomalous up-doming of the base of the gas hydrate stability zone (BGHSZ) is a consequence of the reversibility of the hydrate reaction that makes the formation and dissociation of gas hydrate supremely responsive to changes in local confining pressure or temperature.

**The Martian Natural Gas Play:**

The first requirement for hydrocarbon exploration is determining whether conditions for the generation of sufficient hydrocarbons to comprise a hydrocarbon province exist. Identification of a gas province is based on both direct and indirect evidence. On Earth, direct evidence might consist of the detection of large vents of natural gas from the seafloor or, on land, subaerial mud volcanoes, both of which are good signs that large reservoirs may be present in the subsurface. Indirect methods consist of drill core analyses or remote survey methods such as seismic, magnetic, gravity, and electrical methods, amongst others. While the volume of methane venting from the reservoir is large enough that it could be used as an industrial feedstock, the scale of the methane venting indicates that much larger volumes of methane still reside in the Martian subsurface, and may also indicate an active methane generation system.

With reference to the approximately 2.8 x $10^7$ $m^3$ (or 1 Billion Standard Cubic feet, in oil and gas industry nomenclature) of methane that was vented in a single plume, approximately 2.1 x $10^3$ $m^3$ (13,200 barrels) of high energy density ~3.54 x $10^7$ J/$m^3$ (~950,000 btu/$ft^3$) fuel similar to jet or diesel fuel could have been produced from it and the other available feedstock if the vented methane could have been captured (assuming an average composition of $C_{12}H_{23}$ and 0.84 kg/L density for diesel fuel). In the process of making this fuel, large amounts of hydrogen (2.65 x $10^9$ kg) would also be released, although the reactions that are needed to accomplish these conversions of the basic feedstock into useful products require multiple steps and the hydrogen may be tied up in other types of compounds rather than being available for use in its own right. This same amount of methane, along with the other more readily available components, could be fabricated into many tons of plastic.

**Exploration for Methane Hydrate**

Exploration for methane hydrate and gas deposits on Mars can be conducted with the full panoply of exploration techniques used on Earth, many of which are suitable for autonomous or robotic use.

**Basin Analysis:** Strictly speaking, there are no direct analogs to the many depositional basins of Earth, which are the result of tectonic activity, rapid weathering and erosions, and sedimentation. However, certain areas of Mars are known to possess considerable thicknesses of sedimentary strata. It has also been suggested that an ocean once occupied the northern plains. If so, then considerable erosion and sedimentary deposition may have occurred in the region adjacent to the shoreline, throughout the early history of Mars when water may have been stable on the surface. Basins that would have acted as traps for sedimentary material, and which would have been subject to the generation of secondary porosity within the resulting strata, may have been formed from impact activity and tectonism.

**Geophysical Evaluation:** Reflection and refraction seismic exploration could be carried out on Mars, as it is on Earth, either by humans or autonomously, by robotic spacecraft. Seismic exploration offers the opportunity of not only identifying reflective interfaces, but also determining their bulk and shear moduli by measurement of their p–wave and s-wave velocities and attenuation characteristics. There is a great inventory of analyses and successful techniques, particularly in permafrost areas, that can be applied directly to seismic interpretation on Mars.

**Ground Penetrating Radar (GPR):** GPR is an increasingly important tool in the investigation of a wide range of solar system objects, and is particularly well-suited to the investigation of ice-rich (and. thus, dielectrically low-loss) environments – such as the Martian polar layered deposits, the icy satellites of the outer planets and comets. GPR has resolved details of subsurface structure over a wide range of depths. GPR produces reflection data similar to reflection seismics, and has similar attenuation, penetration, and imaging issues, although they are indicative of electromagnetic, rather than acoustical, properties. However, neither refraction studies nor interval velocities can be determined with GPR from a single orbiting satellite; although both the reflection structure and attenuation may both be determined. It may also be possible to distinguish between water ice and methane hydrate using signal analysis and attenuation characteristics.

**Drilling:** Drilling is the one sure way to identify subsurface geology and composition using sampling and downhole analysis and well understood logging techniques. Autonomous

drilling and coring of at least short boreholes has been done on Earth's seafloors and could be transitioned to the special conditions of the surface of Mars.

**Beyond Mars**

The icy moons of the outer planets (Europa, Callisto, Ganymede, Enceladus, Tethys, Dione, Rhea, Mimas, and Iapetus) may all have water as a considerable proportion of their mass. Both Europa and Ganymede are thought to possess mantle oceans at depth beneath a crust of water ice. Methane is also known to exist on a number of these icy bodies. Where an ice-covered ocean exists, the zone of hydrate stability will extend from the shallow subsurface to a depth of many kilometers beneath the 273 K isotherm, depending on the local hydrothermal/geothermal gradient. An ocean heated from below, however, may have significant convection zones and complex currents that could locally control methane gas hydrate and ice thickness.

**A Hydrocarbon Key to Sustained Human Exploration of the Solar System**

Mars and the moons of the outer planets may have the resources that could sustain human habitation and provide for the acceleration of human exploration and habitation within the solar system. A new paradigm for exploration of the solar system can be based on the identification and utilization of widespread water and hydrocarbons, principally methane, ethane, and propane gas and liquids.

There are some of the practical implications of the recent discovery of large plumes of methane venting from the subsurface of Mars. If sufficient deposits of gas hydrate can be found on Mars, they could be used to fabricate a wide array of materials necessary to support human habitation. Methane could provide the basis for the fabrication of plastics that could be used for constructing facilities and machines, and for making high energy density chemical rocket fuels for both return journeys to Earth and for more distant exploration. The presence of methane hydrate may provide one of the cornerstones for human sustainability on Mars. With its lower escape velocity, and critical natural resources, Mars could be used as a stepping stone to exploration of the solar system.

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